Spatio-temporal variation of fog below the canopy in a subtropical laurel-heath cloud forest of the Garajonay National Park

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ABSTRACT

We study the spatio-temporal variation of fog water dripping from a laurel-heath cloud forest of the Canary Islands in the Garajonay National Park (La Gomera), during a five month period in a line transect. Geostatistical tools are used with this purpose. We find a long term time persistence (2 weeks), indicative of the existence of memory effects in the fog precipitation process. Spatial correlation spans up to 41 meters. Some implications are drawn about the design of a strategy to determine the minimum number of raingauges necessary for characterizing the mean fog water precipitation.

1. INTRODUCTION

Quantifying the amounts of fog captured by vegetation poses several problems because of the large spatial variability both in time and space imposed by the canopy, and the small amounts of water that must be detected. Thus determination of fog water captured by vegetation is not an easy task. Traditionally, two basic methods have been established for measuring fog precipitation: artificial fog catchers and throughfall measurements. While the former may be merely used as an indicator for site characterization (Bruijnzeel, 2001), the latter approach considers the amount of water dripping inside the stand, taking into account the fog water intercepted and evaporated from the wetted canopy. However, large numbers of gauges (fog collectors) are needed to obtain frequent and spatially representative data (Lloyd et al., 1988), although a 'roving' strategy may help to minimize the number of gauges necessary to quantify net precipitation (Holwerda et al., 2006). Thus having *a priori* information about the spatial and temporal distribution of fog dripping from the canopy onto the ground it is desirable for establishing an optimum distribution of gauges (either static or in a roving relocation) for accurate fog capture quantification. This issue has been mostly dealt with in studies of either rainfall or throughfall and stemflow, but there has been limited progress in the understanding of spatio-temporal patterns of fog water impinging on the vegetation and reaching the soil. Thus for example, Loescher et al. (2002) found a range distance of about 45 m estimated from variogram analysis of a radial layout distribution of throughfall collectors in a tropical wet forest of Costa Rica. Keim et al. (2005) claim that patterns of throughfall beneath tree forest stands of conifers and deciduous trees were stable both in time and space, with a spatial correlation within one half and one crown diameter. Recently, Buytaert et al. (2006) showed a large spatial correlation over 4 km but a short temporal correlation over 3 days in rainfall patterns of the south Ecuadorian Andes, although their results must be taken with care because of large data dispersion. In this study we investigate spatio-temporal patters of fog in a line transect of a laurel-heath cloud forest of the Canary Islands in the Garajonay National Park, La Gomera (UNESCO's World Heritage List, 1986). Laurel forests are associated with a windward cloud belt formation, locally known as 'mar de nubes' (sea of clouds), whose upper limit, at about 1200-1500 m, is determined by a well-developed temperature inversion, which prevents moist air from rising up on the north side of the higher altitude occidental islands. This ensures almost permanent humid atmospheric conditions (mean and mode annual relative humidity are 75% and 100%, respectively), favorable for fog formation in a otherwise semi-arid environment such as that of the Canary Islands, located at 28º North in front of the Sahara dessert. Thus, fog in these relic evergreen forests may be relevant for their survival especially during low rainy summer periods (Ritter et al., 2007 this issue). Additionally, climate change predictions point towards a reduction in horizontal precipitation in the Canarian laurel forests (Sperling et al., 2004), thus accurate quantification of this additional water source may be relevant for testing climate change models in the Macaronesian area.

2. **MATERIALS AND METHODS**

The area of study is situated at 1300 m.a.s.l. on the upper border of a small watershed (43.7 ha) within the Garajonay National Park (La Gomera, Canary Islands). The vegetation is mainly composed of wax myrtle-tree heath ('fayal-brezal'), typical of the most degraded areas of the Park usually located at crests and upper-slopes. It is characterized by 7-12 m height, thin and shrubby *Erica arborea* L. trees with a high abundance of epiphytic mosses and lichens. The needle leaves of *E. arborea*, with diameters (∅ = 0.25 mm) on the order of magnitude of the fog droplets (5-50 μm) are efficient structures for the collection of fog droplets by impaction (Ritter et al., 2007 this issue). *Laurus azorica* (Seub.) Franco and *Myrica faya* Ait. broad-leave individuals are also present in the area of study. A line transect was selected within this upper windward plot for installation of 22 autonomous tipping-bucket pluviometers (Davis Instruments Corp., California; 0.2 mm resolution; ∅ = 0.165 m), provided with a Hobo event logger (Onset Computer Corp., Bourne) placed at the following relative distances: 0, 10, 15, 18, 19, 20, 25, 28, 29, 30, 50, 55, 58, 59, 60, 70, 80, 90, 100, 110, 130, and 135 m. Such non-uniform nested spatial distribution was selected in order to characterize both short and large range fog patterns with a reduced number of raingauges. Additionally, laurel species show significant aggregation both at short (2 m) and large (6 m) distances (Arévalo and Fernández-Palacios, 2003), thus constraining fog distribution below the stand in an unpredictable manner. Positions were selected blindly, without paying attention at the vegetation coverage above raingauges, size of tree individuals nearby or plant species present in the neighborhood of each raingauge. Nearby a micrometeorological station provided concomitant data on climatic variables, pluviometry and fog collection by a quarter fog collector above the stand.

Fog spatio-temporal patterns were investigated by means of geostatistical tools (Nielsen and Wendroth, 2003). Previous to this analysis, for non rainy days, daily fog values were standardized to zero mean and unit variance, such that

$$\tilde{X}_{i,t} = \frac{X_{i,t} - \bar{X}_{i,t}}{std(X_{i,t})} \qquad (1)$$

with $X_{i,t}$ being the log transformed cumulative daily fog water amount collected by raingauge i at day t (0 to 149), and where $\bar{X}_{i,t}$ and $std(X_{i,,t})$ are, respectively, the mean and standard deviation of $X_{i,t}$ for all raingauges locations at day t. Skewness of the data can mask its spatial structure making the spatial analysis less reliable (Webster and Oliver, 2001), thus the log transformation was applied to ensure normality. Both directional (0, 45º, 90º and 135º clockwise from the azimuth angle) experimental semi-variograms and Moran's correlograms were computed for the standardized $\tilde{X}_{i,t}$ fog data with the help of the geostatistical analysis program GS+ (version 5.0.3 Beta, Gamma Design Software). A non-uniform lag interval (h = 1, 2, 3, 5, 8, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 80) with 10º angular tolerance was selected for the analysis. Models were fitted to experimental variograms using a global optimization algorithm (Ritter et al., 2004). Fitted models are characterized by a *nugget* (random variation at zero lag), a *sill* or maximum value of variation and a *range*, separation distance at which the sill is reached. Zero fog data values were treated in three different ways: case a) zeros were replaced by a value half the raingauges's resolution (since the logarithm of zero is undefined); case b) zeros were removed from the data set and treated as no data for the subsequent geostatistical analysis; a third case was also considered, such that fog data was treated discretely, i.e. fog values ≥ 0.2 mm were set to unity, and zero otherwise (case c). While the latter aims studying spatio-temporal fog patterns qualitatively, i.e. presence/absence of dripping fog, without paying much attention at the amount of fog collected, case a) takes into account the size of fog collected and considers that those locations were fog is not measured (< 0.2 mm) retain information that must be incorporated into the analysis (correlations between locations with no measurable fog are assumed to be relevant, since they provide information about the time scale of inter-fog periods), in contradistinction to case b) where only patterns of detectable fog are considered.

3. **RESULTS**

For the three cases described above we investigated variance and auto-correlation trends, in both time and space directions. In case a) and b) a decreasing autocorrelation trend with respect to time was observed (Fig. 1a-b) and no clear spatial dependency i.e. purely random or *nugget* effect (not shown). Correlation spans over a larger time in case a) than case b) (c.f. Fig. 1a and 1b). By contrast case c) shows both time and spatial correlation structure, although more clearly in the space direction (Fig. 1c-d). These differences in the spatial correlation of case a), b) and c) may be due to the low amounts of dripping fog that must be detected. The random component imposed by wind, delay effects, randomness of the vegetation structure, forest gap changes, funneling and shading effects, etc., and the microvariance (i.e. spatial variation occurring at distances closer than the sampling spacing) mask the possible existing spatial trends. Only in qualitative terms (i.e. fog vs. no fog locations) the spatial structure shows up (Fig. 1d). This has also implications in the design of a strategy to determine the minimum number of raingauges necessary for characterizing the mean fog water, since when spatial correlation is present, the required number of raingauges must be increased, because the amount of information in any sample fog measure is diminished (Mulla and McBratney, 2002). Concentrating in case c) an exponential model

$$\gamma(h) = C\left[1 - \exp(-3h / a)\right] \qquad (2)$$

was best fitted to time and scale semi-variograms (table 1). In (2) $\gamma(h)$ is a variance measure, C is the *scale* (=*sill* - *nugget*), and a is the *range*.

Table 1. Parameter values fitted to time and space variograms (2) in case c).

Direction	nugget	sill	range	r^2
time	0.16	0.25	13 days	0.65
space	-0.04	0.20	41 m	0.96

The range obtained (41 m) for the space-variogram is of the same order of previously reported values for throughfall (Loescher et al., 2002). By contrast, the time-variogram range (13 days) is indicative of a larger temporal correlation as compared to that reported for other precipitation phenomena such as rain (<3 days).

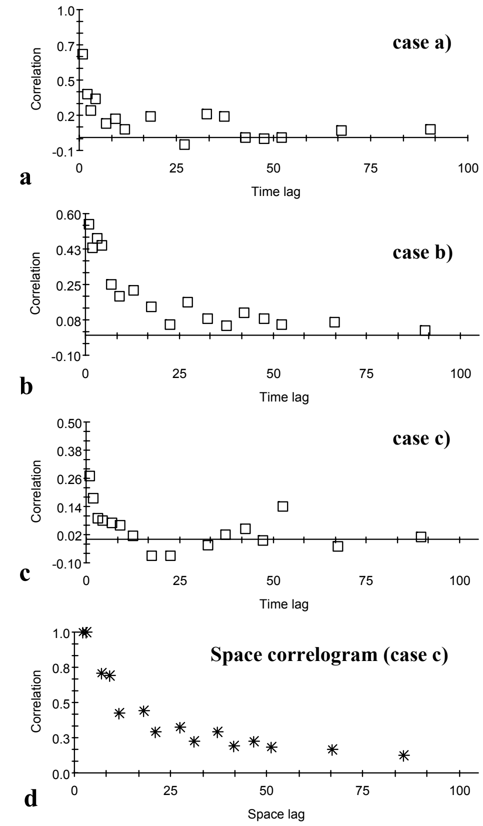

Figure 1. Time correlograms (1a-1c) for the three different cases considered (□). Also shown (1d) space correlogram (*) for case c).

In this respect temporal behaviour of fog precipitation is closer to streamflow (Skøien et al., 2003), but the two process are somehow similar in that they resemble a cascade of 'filling' and 'emptying' reservoirs. Horizontal precipitation is a complex time-delay process whereby small fog droplets after impaction and sedimentation, join to form larger drops, which either divert to the stems or are funneled towards drip points, falling under the influence of gravity. Additionally, fog capturing is in dynamic competition with the evaporation rate. This, together with other effects such as the vertical gradient of wind speed, both orientation and sheltering of collecting elements, make the small amounts of water droplets that must convey to a raingauge below the canopy, to be correlated over larger time lags.

When both time and space components are taken into account, a complex picture in the spatio-temporal variance plane appears (Fig. 2). At an azimuth angle of 154º a major axis of anisotropy may be identified.

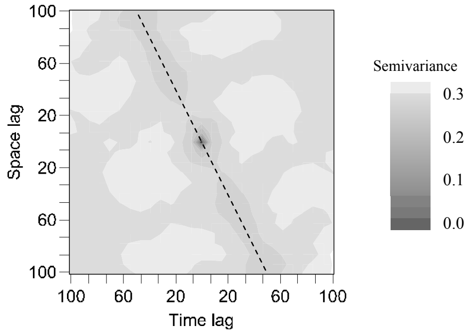

Figure 2. Spatio-temporal variogram surface for case c). The dotted line indicates the principal anisotropic axis.

A log-log plot of the semi-variance vs. the separation distance at 135º clockwise from the 154º azimuth angle, suggests that the scaling in the direction 289º is fractal, rendering a Hausdorff-Besicovitch dimension D=1.939 (s.e.=0.081; r^2=0.978; Fig. 3). A fractal scaling implies that we can determine the variance of fog at one scale based on the variance at any other scale (self-similarity), and it is thus an indication of long range memory in time and/or space, also known as the Hurst phenomenon.

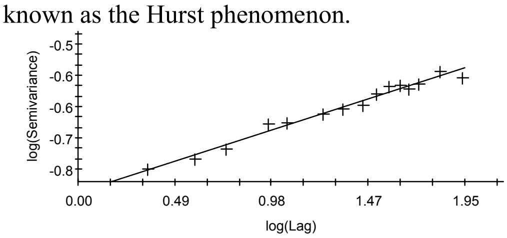

Figure 3. Log-log plot of semi-variance against lag distance in the direction 289º for case c).

4. CONCLUSIONS

A geostatistical analysis of fog precipitation below a laurel-heath forest in the Garajonay National Park revealed a long-range two-week time dependence, and 41 m space correlation scale. Hence, fog precipitation may be resembled to other time-delay long range memory hydrological process, such as runoff or streamflow, closer than to gross rainfall. The spatio-temporal picture of dripping fog variation reveals a complex structure, with a major axis of anisotropy at 154º. Thus sampling strategies may take into account this scenario, since when spatial correlation is present, the required number of raingauges must be increased,

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